Narrow Linewidth CPT Signal in Small Vapor Cells for Chip Scale Atomic Clocks*

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Abstract — **We report our measurement of coherent-population-trapping (CPT) signal linewidths in small vapor cells, which are desirable for chip scale atomic clock (CSAC) applications. The linewidths are measured in both rubidium vapor cells and cesium vapor cells. Using a micro-machined silicon absorption cell (diameter = 1.7 mm, length = 2 mm), we demonstrate a sub-kHz linewidth (FWHM) of the clock transition in the ^{133}Cs atom ($|F = 3, m_F = 0\rangle \leftrightarrow |F = 4, m_F = 0\rangle$). The measured intrinsic linewidths (FWHM = 777 Hz for Cs and FWHM = 1496 Hz for Rb) of the cells agree with the calculated results.**

Keywords: ***coherent-population-trapping; atomic frequency standards***

I. INTRODUCTION

The short-term stability of an atomic frequency standard is determined by the signal-to-noise ratio (S/N) and the line-Q of the clock transition in the chosen atomic species. The latter is inversely proportional to the linewidth of the atomic transition. In a vapor cell based atomic frequency standard, the importance of the clock transition linewidth is even greater when the dimensions of the absorption cell approach mm or sub-mm, such as in the chip scale atomic clock (CSAC).

The elimination of the direct microwave excitation in a coherent population trapping (CPT) based atomic frequency standard promises a smaller, simpler, and less expensive device [1]. For example, a CPT resonance signal with a FWHM linewidth of 280 Hz and with a signal contrast of 4.4% is demonstrated using a cm-scale ^{87}Rb absorption cell [2]. Consequently a short-term stability of $1.3 \times 10^{-12}\,\tau^{-1/2}$ is also demonstrated using the same ^{87}Rb cell [2].

Hence it is of great interest to study the CPT resonance signal in small absorption cells, especially for the chip scale atomic clock application. In the following sections, we discuss the limiting factors for the CPT resonance linewidth and then present the results of the linewidth measurement of CPT resonance signals in mm-scale absorption cells.

II. LIMITING FACTORS OF CPT RESONANCE LINEWIDTH

In this section we examine the limiting factors of the CPT resonance signal in a compact vapor cell with ^{87}Rb atoms or ^{133}Cs atoms. The observed linewidth (HWHM) of a CPT resonance signal can be written as

$$\gamma_2^{\text{observed}} = \gamma_2^{\text{cell related}} + \gamma_2^{\text{spin exchange}} + \gamma_2^{\text{laser power}} \quad (1)$$

The explicit expression of the first term in (1) depends on the characteristics of the cell walls and whether the cell contains buffer gas. For a cell with coherence-destroying surfaces and buffer gas, the first term in (1) is given by

$$\gamma_2^{\text{cell related}} = \gamma_2^{\text{diffusion}} + \gamma_2^{\text{buffer gas}} , \quad (2)$$

where $\gamma_2^{\text{diffusion}}$ represents the linewidth determined by the diffusion process while $\gamma_2^{\text{buffer gas}}$ describes the de-phasing process due to the collisions between the alkali atom (^{87}Rb or ^{133}Cs) with the buffer gas molecules [3, 4]. For a cylindrical cell with a radius of R and a length of L, we can further write (2) as

$$\gamma_2^{\text{cell related}} = D\left\{\left(\frac{2.405}{R}\right)^2 + \left(\frac{\pi}{L}\right)^2\right\} + n_{\text{buffer}}\bar{v}_r\sigma_2 , \quad (2a)$$

using only the lowest order diffusion mode. In (2a) D is the diffusion constant, n_{buffer} is the density of the buffer gas molecules, $\bar{v}_r$ is mean relative speed, and σ_2 is the de-phasing collision cross section. The impact of the small dimensions of the cell on the linewidth of the CPT resonance signal is shown explicitly in the first term of (2a). Since the diffusion constant, D, is inversely proportional to the buffer gas pressure in the low buffer gas pressure region, higher buffer gas pressure could be used in a small vapor cell to reduce the linewidth of the CPT resonance signal. This approach is limited by the contribution of the second term in (2a) and the larger temperature coefficient caused by higher buffer gas pressure.

The second term in (1) can be written as

$$\gamma_2^{\text{spin exchange}} = \frac{1}{2} n_{\text{atom}}\bar{u}_r\sigma_{\text{spin exchange}} , \quad (3)$$

where n_{atom} is the density of alkali atoms, $\bar{u}_r$ is the mean relative speed, and $\sigma_{\text{spin exchange}}$ is the cross section for the spin exchange collisions [3, 4]. In order to obtain a CPT resonance signal with a good signal-to-noise ratio, it is desirable to keep

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an adequate optical attenuation of the laser beam in the cell even when the dimensions of the absorption cell decrease. Hence the broadening due to the spin exchange collisions in (3) is approximately proportional to the reciprocal of the length of the absorption cell.

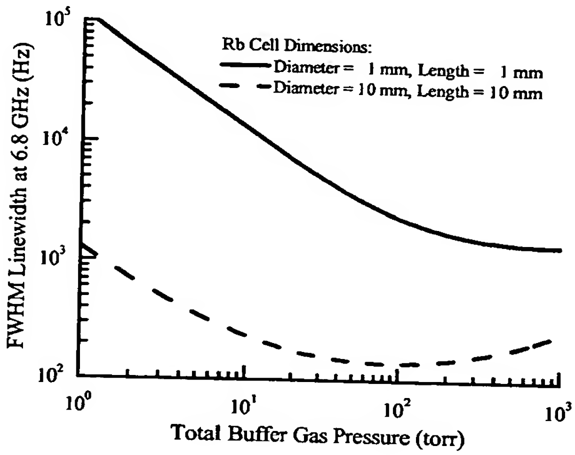

Figure 1. Calculated intrinsic linewidths of ^{87}Rb atom vs. total buffer gas pressure (Ar-N_2 mixture) in a mm-scale absorption cell and in a cm-scale absorption cell. See text for discussion.

The third term in (1) has the form of

$$\gamma_2^{\text{laser power}} = \frac{\omega_R^{\;2}}{\Gamma} \propto I_{\text{laser}} \;, \tag{4}$$

where ω_R is the Rabi frequency, Γ is the linewidth (FWHM) of the optical transition, and I_{laser} is the laser intensity. Experimentally, this term can be determined by measuring linewidths with various laser beam intensities.

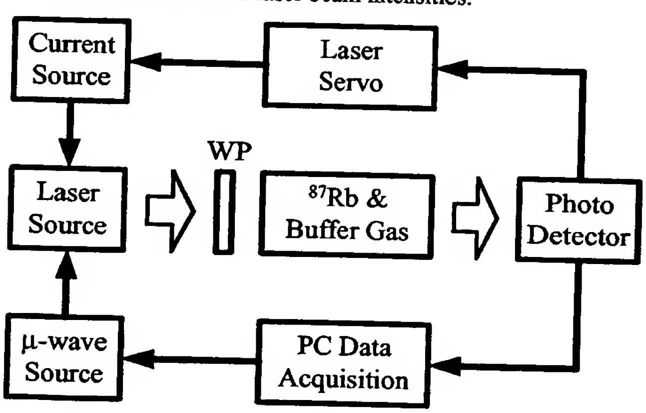

Figure 2. Experimental setup for measuring CPT resonance linewidth in the Rb cell (diameter = 2 mm, length = 2 mm). WP is a λ/4 wave plate. See text for discussion.

We define the intrinsic linewidth of the absorption cell as the linewidth determined by the first two terms in (1). However in order to obtain a CPT resonance signal with a good signal-to-noise ratio, the measured linewidth is always broader than the intrinsic linewidth of the cell.

Using the first two terms of (1), Fig. 1 shows the intrinsic linewidths of the clock transition in ^{87}Rb atoms versus the buffer gas pressure in two absorption cells. It is seen that for the mm-scale absorption cell the linewidth approaches 1 kHz only at a buffer gas pressure of ~ 1000 torr, which could cause a large temperature coefficient of the frequency standard.

III. Experiments

A. Linewidth measurements with a ^{87}Rb vapor cell

The Rb absorption cell is made of glass. Both the diameter and the length of the cell are 2 mm. The inner diameter of the fill tube is 0.5 mm so that the cell geometry is well defined. The cell is baked under high vacuum for outgassing before it is

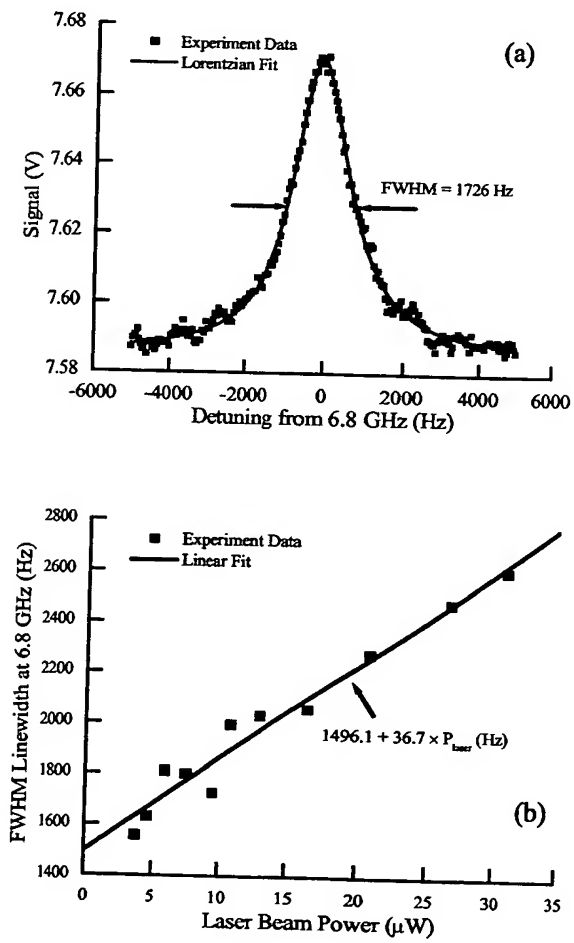

Figure 3. Experimental results using a glass ^{87}Rb vapor cell (diameter = 2 mm, length = 2 mm). (a) A typical CPT resonance signal at the clock transition frequency (6.8 GHz) of ^{87}Rb. (b) The linear fit of the measured linewidths versus the laser beam power. See text for discussion.

loaded with ^{87}Rb vapor and buffer gas (Ar-N_2 mixture). The total buffer gas pressure is 23 torr.

Fig. 2 is a schematic diagram of the experimental setup for measuring the linewidth of the CPT resonance signal in the glass Rb cell. To obtain high signal contrast, the D_1-line ($\lambda \approx$ 795 nm) is chosen to excite the coherence-population-trapping [5, 6]. An external cavity laser is directly modulated at ~3.4 GHz. The ±1st order sidebands are used to generate the CPT resonance signal. The modulation index is chosen such that the light shift (ac Stark shift) is suppressed by the higher order sidebands during the measurements [7, 8].

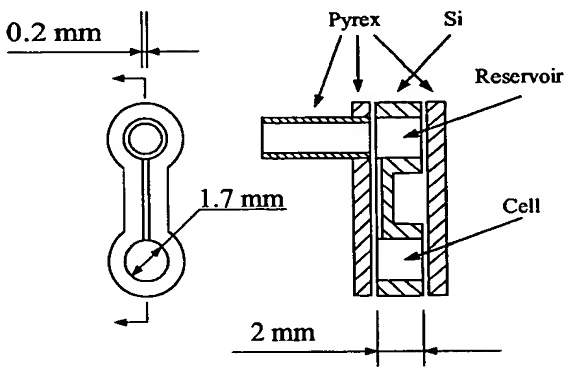

Figure 4. Dimensions of the micro-machined Si cell. Extra Si structure outside the cell body is used to support the Pyrex windows. See text for discussion of the Si etching process and bonding process.

Fig. 3(a) shows a typical CPT resonance signal. A Lorentzian line shape is fit to the experiment data. As shown in Fig. 3(a), the Lorentzian line shape describes the CPT resonance signal well. The CPT resonance linewidths are measured at various laser beam intensities. Fig. 3(b) shows the measured linewidth (FWHM) versus the total laser beam power. A straight line is fit to the experiment data in order to extrapolate the intrinsic linewidth (FWHM = 1496 Hz at 6.8 GHz) of the glass Rb cell.

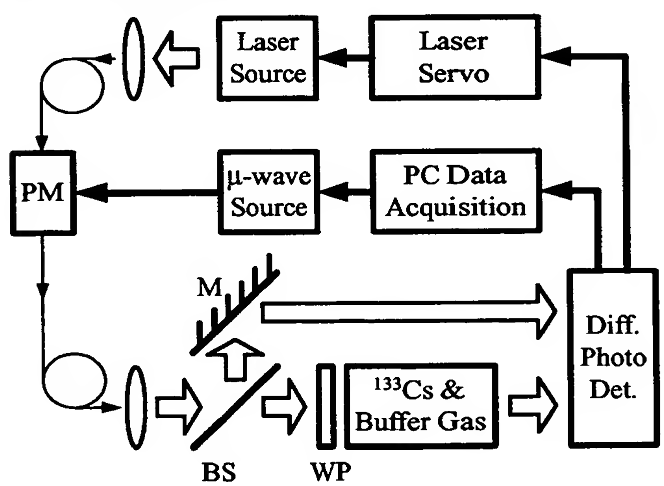

Figure 5. Experimental setup for measuring CPT resonance linewidth in the Cs cell (diameter = 1.7 mm, length = 2 mm). M is a mirror, BS is a beam splitter, and WP is a $\lambda/4$ wave plate. See text for discussion.

B. *Linewidth measurements with a ^{133}Cs vapor cell*

Fig. 4 depicts the dimensions of a micro-machined Si cell used in the measurements of the CPT linewidth with ^{133}Cs vapor. A 4 mm long channel with a cross section of 0.2×0.2 mm^2 connects the reservoir and the absorption cell. The diameter and the length of the cell are 1.7 mm and 2 mm, respectively.

The cell is fabricated using a three wafer, anodic bonding process. Front to back alignment marks are etched on both sides of a 2 mm thick silicon wafer. Using standard positive photoresist, the wafer is patterned with a 200 µm wide and 4 mm long channel. This channel is etched 200µm into the silicon wafer using deep reactive ion etching (DRIE) with the Bosch process. The cell and reservoir are patterned using a thick photoresist process, and etched 1 mm into the wafer using DRIE. The patterned side of the wafer is then anodically

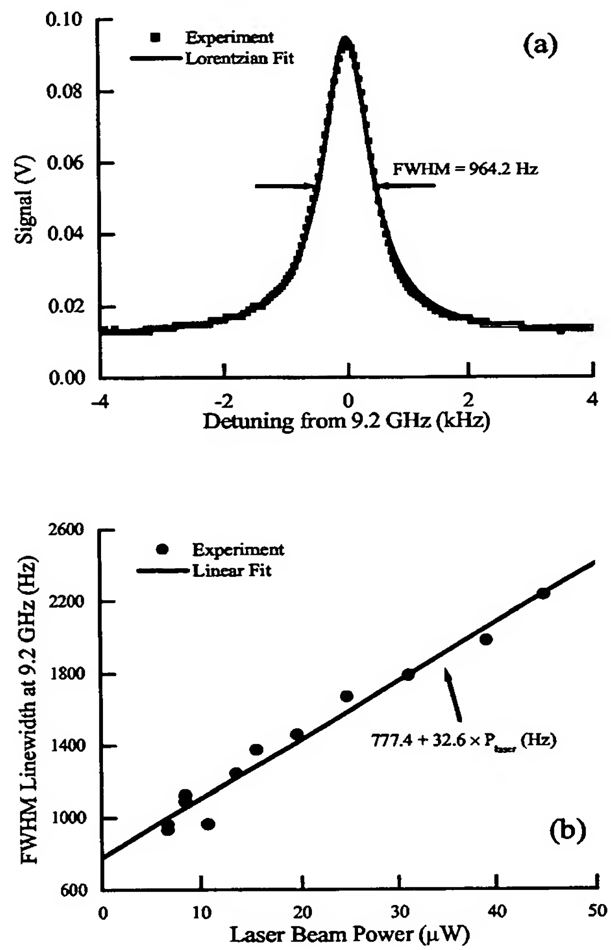

Figure 6. Experimental results using a micro-machined Si cell (diameter = 1.7 mm, length = 2 mm) for ^{133}Cs atoms. (a) A typical CPT resonance signal (FWHM = 964 Hz) at the clock transition frequency (9.2 GHz) of ^{133}Cs . (b) The linear fit of the measured linewidths versus the laser beam power. See text for discussion.

bonded to a Pyrex wafer. After bonding, the wafer is flipped over and patterned again with the cell and reservoir. This pattern is then etched the rest of the way through the wafer (approximately 1 mm) using DRIE until it meets up with the previously etched pattern from the other side. The wafer is then anodically bonded to a second Pyrex wafer that has been previously processed with ultrasonically drilled through holes. The final step of the process is to attach a Pyrex fill tube to the drilled hole in the Pyrex wafer using a commercially available glass frit preform. Then the cell is loaded with ^{133}Cs vapor and a buffer gas (Ar-N_2 mixture) with a total pressure of 70 torr.

The experimental setup for measuring the linewidth of the CPT signal in the cell is shown in Fig. 5. The D_2-line ($\lambda \approx 852$ nm) is used in this set of experiments due to the lack of an appropriate laser at $\lambda \approx 895$ nm. A DBR laser and a traveling wave phase modulator generate the necessary sidebands for CPT generation as well as for light shift suppression [7, 8]. A differential photo detector is used for observing the CPT signal so that the large part of the dc background is suppressed.

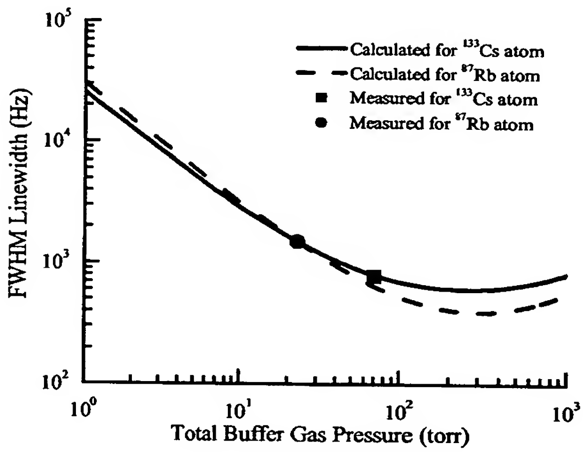

Figure 7. Comparison between the calculated linewidths and the measure linewidths for both ^{133}Cs atom and ^{87}Rb atom. The Cs absorption cell is a micro-machined Si cell (diameter = 1.7 mm, length = 2 mm). The Rb cell is a all glass cell (diameter = 2 mm, length = 2 mm). See text for discussion.

Fig. 6(a) shows a sub-kHz linewidth (FWHM) CPT resonance signal in the micro-machined cell. Multiple linewidth measurements are taken at various laser beam intensities. Fig. 6(b) shows a linear fit of the measured linewidth versus the laser beam power. The derived intrinsic linewidth for the micro-machined cell is 777 Hz (FWHM) at the clock transition frequency (~9.2 GHz) of the ^{133}Cs atom.

C. *Comparison with the calculations*

Fig. 7 plots the calculated intrinsic linewidths of both cells using the experimental conditions. The experimental linewidths are also shown in Fig. 7. It is seen that the experimental results agree well with the calculations, validating the scaling of the linewidth formulation to m-scale dimensions.

IV. Summary

We present narrow linewidth CPT resonance signals measured in a glass cell with ^{87}Rb vapor and in a micro-machined Si cell with ^{133}Cs vapor. In the latter case, a sub-kHz linewidth at the clock transition frequency (~9.2 GHz) is observed. The experimental results agree with the calculations. Thus the calculation method can be used to guide the design of absorption cells in future work.

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